A review of small island hydrogeology: progress (and setbacks) during the recent past

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Abstract: Careful resource management is needed on small inhabited islands because demand can stress finite fresh groundwater reserves. Managers need to be informed how the groundwater system functions so that they can optimize the resource use and safeguard it from abuse. Hydrogeological investigation in small islands is broadly similar to basin studies on the mainland but small island scale coupled with data scarcity (including effective rainfall, permeability and baseflow) inhibit conventional groundwater flow modelling. Coastal and offshore baseflow measurement is the greatest uncertainty and research aims to better constrain its determination in the future. Small island hydrogeological investigations are challenging and aquifers can be classified as high-elevation hard fractured rock systems and low-relief karst limestone and sand islands. Although small island hydrogeological techniques have advanced considerably in the last 20 years, they must improve again in the future to help the many communities living in small island states that receive only erratic and unreliable rainfall recharge.

Small Island Developing States are recognized by the United Nations as having special challenges for achieving sustainable development (Watson *et al*. 1998). They are characterized by small island countries with challenges that include low population, lack of resources, remoteness, susceptibility to natural disasters, excessive dependence on international trade and vulnerability to global development. Sustainable development is inhibited by lack of economies of scale, high transportation costs, and public administration and infrastructure provision that collectively place an expensive burden on small populations (Moglia *et al*. 2008). Above all, the provision of fresh potable water, and in particular groundwater, to small island communities underpins all other activities.

Understanding the water budget in a variety of physical environments on small islands has greatly improved with the modern-day application of groundwater flow modelling. This not only informs data gathering, to ensure that sensible monitoring is taking place and that data gaps are being plugged, but also tests the conceptual understanding of the groundwater system and the water budget. However, not all porous media groundwater flow models can cope with the scale of small karst limestone or fractured hard rock islands and bespoke modelling code may be preferable (Praveena *et al*. 2010).

There have been setbacks as hydrogeologists realize that they cannot measure some critical elements of the water budget directly. Groundwater discharge to a foreshore can often be seen at low tide, and specific electrical conductivity shows it to be a brackish mix of seawater and groundwater; the discharge of groundwater to the foreshore and the sea can be determined by application of a Darcy slice model only if data are available. Even effective rainfall cannot readily be measured on some ‘high rise’ islands where windward and leeward, coastal and interior may differ greatly and accurate monitoring is not practicable. An extreme example is the rainfall gradient of 1000 mm a^{-1} km^{-1} between the coast and the upland interior on Raratonga in the Cook Islands. On the positive side, however, an island does have a coastline, clearly delineating the project area. The blue line, to all intents and purposes, is a near constant head boundary; the maritime tidal signal generally only penetrates a few tens of metres inland except in karst limestone.

It is two decades since Falkland (1991) prepared his seminal treatise on small island hydrogeology. Subsequent advances in analysis and understanding of small island hydrogeology include new tools that have become available, not least through the application of modern-day computing power, but also, for example, the development of sophisticated and accurate groundwater dating techniques (e.g. using chloro-fluoro-carbon species; Stuart *et al*. 2010), for groundwater residence times of only a few decades, and a focus on holistic analysis of island hydrology and groundwater vulnerability.

It is appropriate to consider some of the new investigatory techniques within the context of the issues that have arisen in the last 20 years, including the following: (1) demand and supply require management; (2) freshwater resources on small islands are, by definition, shallow (vulnerable to contamination from on-site sanitation, poor land use practices and seawater intrusion); (3) the Ghyben–Herzberg ‘freshwater lens’, a theoretical model that cannot be applied universally, is now competing with dynamic dispersion models; (4) runoff and groundwater discharge cannot be measured directly as they would be with an inland catchment; (5) impending sea-level rise will elevate base levels and change the freshwater storage capacity.

The vision of the government geologist undertaking borehole siting surveys in the Lesser Antilles from the Geological Survey Department’s schooner (Martin-Kaye 1959) is sadly no longer the backdrop for most island investigations. Harsh maritime environments, complex hydrogeology, and the dynamics of the island provide the hydrogeologist with challenges and problems to be solved that are unlike those that arise on the principal aquifers on the mainland.

This paper reviews current understanding of small island hydrogeology in the context of environmental and sociological demands. Case studies and examples are cited to illustrate small island groundwater problems. Those associated with evaluating and assessing island hydrogeology are highlighted, along with appropriate techniques and methods that can be applied. The overall

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objective of this paper, however, is to stimulate interest in a fascinating part of hydrogeology that is not widely appreciated.

Small islands

There are 50000 small tropical islands in the Pacific, Indian and Atlantic oceans, of which about 8000 are inhabited (White *et al*. 2007), the majority to be found in the Pacific and West Indies (Fig. 1). There are numerous small islands in the temperate climates, including, for example, several tens of thousands in the Baltic Sea alone, and 145 populated small islands around the coasts of the British Isles, although 20 of these each had fewer than 10 permanent residents reported in the last census (see http://census.ac.uk). Many of these small islands enjoy high seasonal rainfall yet are faced with severe water problems, especially on the low coral atoll islands (Table 1). It is noticeable that the high-elevation islands promote significant runoff whereas many low-elevation islands have virtually no runoff. The tropical island paradox is human need competing with groundwater-dependent ecosystems; the water requirement to support subsistence crops such as coconuts, swamp taro, breadfruit and pandanus has a severe impact on the water budget (White *et al*. 2007). This paradox is repeated in temperate island communities where, for example, nitrate applied to early potato crops can cause long-term degradation of groundwater quality (Robins & Smedley 1994). The need for detailed understanding of small island groundwater systems is great, and this understanding must be applied both to the top-down management of island resources and the bottom-up enlightenment of the community on the care of the resource.

Small islands studies inevitably draw on experience gained on larger islands such as Britain and New Zealand, which in turn draws on experience from continental studies notably in North America, Australia and continental Europe (Matalas 1987). There are inherent dangers in this information chain because small islands cannot ‘affect and be affected by atmospheric processes of the air masses moving over them’ (Matalas 1987) and are of a size where the time of response of even the larger surface water catchments to a rainfall event is measured in hours rather than days in an environment where every part of the island enjoys a maritime climate (Mowlabucus 2002).

Coast length to island area ratio is a useful indicator of maritime influence. Other defining properties are island shape, maximum and average elevation, climate, runoff (perennial or ephemeral), groundwater transport and storage, vegetation and land use. Dynamic factors include sea-level rise (which affects the base level), demand for water and engineered change. Engineering, intended to be positive, may have a serious negative impact, as for example the detrimental effect the Grand Lucayan Waterway had upon the freshwater lens on Grand Bahama (Robins 2012). More successful engineering includes the subsurface perimeter dams being installed in coral reef limestone on Ryukyu Island in Japan, which are designed to retain groundwater from discharging to the sea and to prevent seawater ingress (Sakura *et al*. 2003). But the same basic hydrogeological rules that apply to continental groundwater investigations also apply to studies of groundwater in small islands; it is the relative importance of the various processes that are different as well as the problems that need to be solved.

A guide to the hydrological classification of small island types is a useful precursor to understanding the problems faced on small islands. Very small islands are excluded from these typologies as being too small in area to sustain a usable freshwater resource; these include the sand cays of the West Indies and some of the smaller atolls of the Pacific and Indian oceans, where water supply depends primarily on rainwater harvesting.

A number of typologies have been published, some on a regional scale whereas others have attempted a more universal classification. A generic typology based on Falkland (1991) is typical (Robins & Lawrence 2000): (1) geologically young ‘high rise’ volcanic islands: Hawaii type; (2) geologically older ‘high rise’ volcanic islands: St. Helena type; (3) near continental bedrock islands: Channel Islands type; (4) low-elevation coral limestone islands: Bermuda type; (5) recent calcareous sedimentary islands: Turks and Caicos type; (6) upland limestone islands: Malta type.

Each group of island type can be subdivided. Vacher & Quinn (2004) provided a threefold classification for limestone islands based on the premise that carbonate rocks are generally highly permeable and that hydraulic conductivity can increase by up to two orders of magnitude as carbonate formations age and become karstified: (1) composite islands: coastal carbonate wedges thinning inland onto outcropping non-carbonate rocks, as in Guam or Bermuda; (2) dual aquifer carbonate islands: these include Holocene sand over reef limestone in which the hydraulic conductivity in the sand is two orders of magnitude lower than in the limestone, as in Bahamas; (3) islands with cross-island variation in hydraulic conductivity, such as Bermuda.

In the case of ‘high rise’ volcanic islands Robins *et al*. (1990) provided another threefold division based on work in the West Indies (Fig. 2): (1) islands with pyroclastic fringes with groundwater present at high elevations (e.g. Grenada); (2) islands with pyroclastic deposits where the effective rainfall cannot maintain throughflow to the coast (e.g. Beef in the British Virgin Islands); (3) islands without pyroclastic deposits in which groundwater occurs only in the fractured volcanic rocks (e.g. the Grenadines and Tortola).

Other workers have classified small islands according to groundwater properties: recharge, storage, yield and water quality. Matalas & Grossling (1996) adopted a different approach using geography, hydrology and economic prospects, which were brought together as a ‘wetness index’; a worldwide sample of 1000 islands largely fell across the intermediate classes with only 181 islands classed as ‘dry’ and 124 as ‘wet’. However, the key to island typology is high rise and low elevation islands and all other categories are subdivisions of this basic classification.

There are numerous pressures on small islands. Although most support only small populations, a small number are densely populated. Malé in the Republic of Maldives, for example, has an area of just 1.3 km^2 but supports 60000 people (Falkland 1991). Tourism can enhance water demand in parallel with island economy and can make solutions such as desalination become viable. Care needs to be taken to prevent pollution of the freshwater lens, which the rest of the island population need, and special care is needed in siting potentially polluting activities such as waste water treatment systems, fuel stores, dry cleaners and laundries, the location of which might be condoned on a larger mainland aquifer with a deeper vadose zone and larger storage and diffusion properties. Perhaps the greatest threat of all is seawater intrusion, which can be avoided only where population density allows sensible management based on sustainable supply, in the worst case from thin freshwater lenses floating over seawater.

Current groundwater issues

Management of demand and supply

Demographics and increased per capita demand for water are putting considerable stress on the available water resources of many small islands. Water consumption in many of the poorer atoll communities varies between 30 and 50 $l\,day^{-1}$ per person and demand increases in parallel with wealth. Waste water may

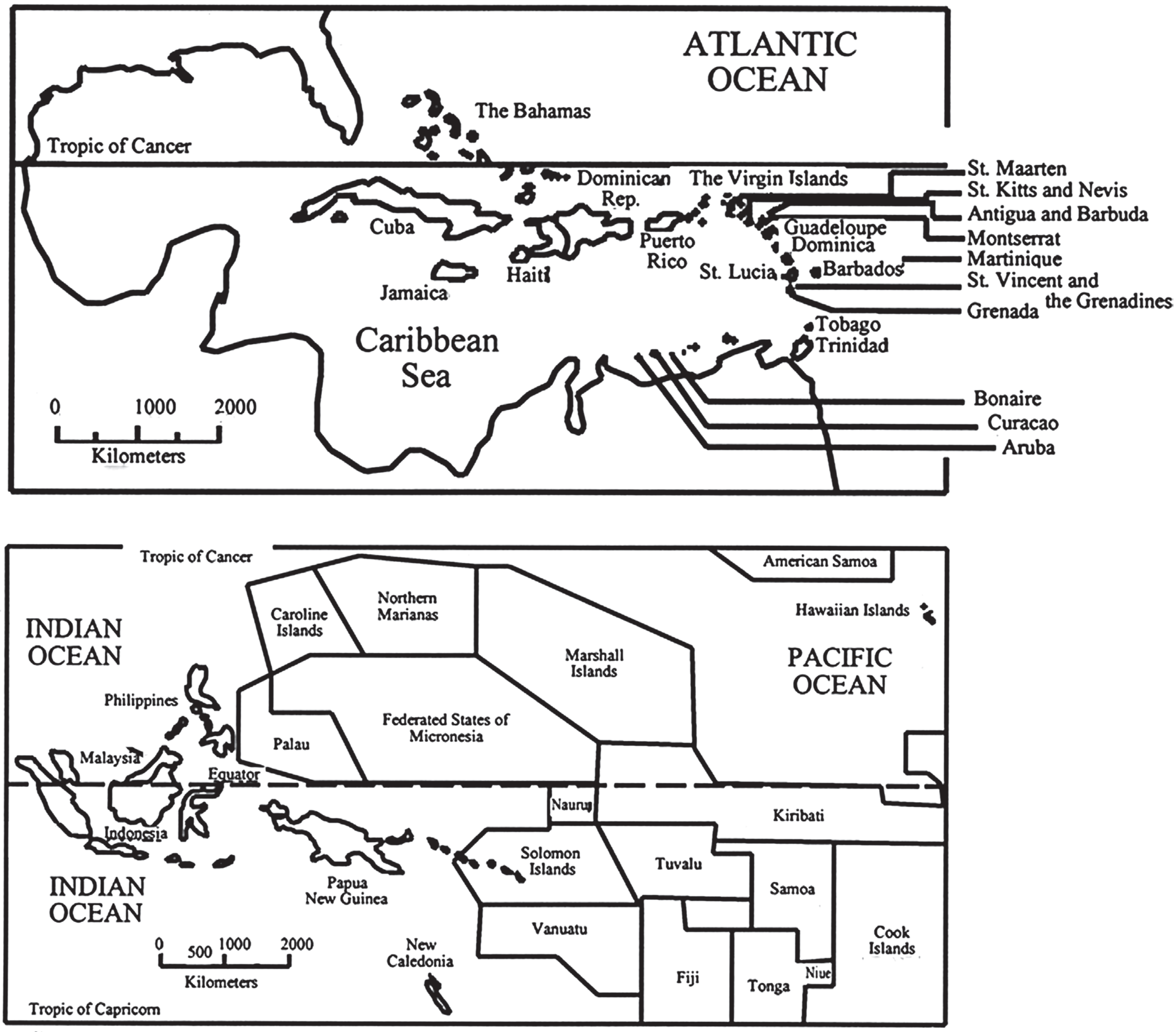

Fig. 1. Small island nations in the Pacific and West Indies.

be discharged to household gardens; pit latrines provide a focused pathway for the passage of bacteria and pathogens to shallow groundwater. Clearly, careful and targeted management of the finite water resources available to island communities is essential to their well-being. Policies may need to include rainwater harvesting, although more expensive augmentation schemes, such as desalinization of seawater, may not be achievable.

In some atoll communities the government has declared groundwater reserve areas in which settlement is prohibited and land use restricted. These are promoted in some Pacific islands by government payment to reserve landowners acting in their designated role as reserve custodians (White *et al.* 1999). Freshwater reticulation systems are open to abuse and often leak. Where supplies are intermittent taps are left open in the hope that the supply will later resume, a situation that can lead to severe wastage. A novel approach to conservation has been introduced on the densely populated island of Kiribati in the Pacific whereby the state delivers a continuous trickle feed into a 500 l tank at each qualifying household and it is up to the household how it uses the water (Metutera 2002).

At the core of many island groundwater management problems are traditional water ownership ‘rights’ and ‘laws’ inherent in land tenure. These rights conflict with the needs of urbanized island societies. In Jersey in the British Channel Isles (Les Isles de Manche) water passing across, or groundwater below belongs to the landowner under traditional Norman Law. The agricultural lobby resisted proposals for new environmental laws, now enacted, that were essential to sustain the economic future of the island. Of these, the Water Resources (Jersey) Law 2007 requires registration of smaller groundwater abstractions and licensing of larger ones. Nevertheless, farmers were not affected by the new management framework and all have benefited from protection of their water sources from derogation by neighbours. However, the transition from informal water ownership rights to a managed structure may not be so readily accomplished on islands where farmers are entrenched, and payment of compensation may be needed

Table 1. *Examples of small island water budgets in order of declining rainfall for both high- and low-elevation island types (after Robins & Lawrence 2000)*

Island	Long-term average rainfall (mm)	Distribution of rainfall (%)		
		Actual evaporation	Groundwater recharge	Runoff
High-elevation islands				
Maui, Hawaii	2850	26	34	40
Zhoushan Islands, China	1350	56		44
Norfolk Island, Australia	1320	62	30	8
Antigua, West Indies	1100	90	2–10	0–8
Jersey, Channel Islands	877	60	5	35
Kahoolawe, Hawaii	767	70	10	20
Menorca, Spain	600	69	18	13
Malta	500	70	24	6
Santiago, Cape Verde	250	50	17	33
Low-elevation islands				
Guam, Mariana Islands	2200	62	38	0
Nuie, Pacific	2050	69	31	0
Nauru, Pacific	2000	60	40	0
Malé	1900	56	42	2
Bermuda	1450	73	27	0
Anguilla, West Indies	1100	95	5	0
Kiribati, Pacific	847	75	25	0
St. Croix, West Indies	750	98	2	0

to encourage restricted land use practices to promote conservation of water.

Awareness building and consultation with the communities are essential precursors to water reform on small islands (Crenman 2002). Natural progression towards reform includes water sector assessment, an agreed water vision, development of a water action agenda, institutional reform and investment, and extensive dialogue with potential investors and donors alike. Fundamental to water reform is a thorough understanding of the water resource, commonly a groundwater reserve sustained by direct rainfall recharge over a small land area, and how best to optimize the use of the reserve for the benefit of the island community as a whole. This requires a detailed conceptual model and water budget assessment tested by a suite of appropriate investigatory techniques.

The role of the hydrogeologist in support of groundwater management in small islands is to acquire a comprehensive conceptualization of the groundwater flow system and to attain a broad understanding of the likely range of the annual water budget. The hydrogeologist needs also to be able to inform managers from this understanding. A variety of tools are available, ranging from hydrogeological maps and schematic ‘cartoons’ at one end of the spectrum to geographic information system (GIS) format data systems to underpin decision support systems at the other. The human element must not be overlooked and the hydrogeologist must be prepared to write informal articles for general consumption, to present workshop information to civil servants and politicians at a more informed level, and be able to present detailed technical information and arguments to scientific peers. The most important dissemination target is the general public, who need to be informed of the delicate and finite nature of their water resource and how they can help to safeguard it, both now and for their sons and daughters.

Groundwater vulnerability

Groundwater in islands, especially low-lying limestone islands, is vulnerable both to natural processes and anthropogenic abuse. Critically the water table is only shallow and is immediately vulnerable to chemical or biological surface pollutants (Dillon 1997). Even dry deposition of salt can arrive at the water table within 2 h of the onset of the first rains where the water table is only 2 m below ground in a karst limestone reef island.

Drought, storms and climate change can severely affect quantity and quality of the groundwater reserve. Periodic drought and lack of a reliable rainy season reduce the freshwater store as baseflow discharge and abstraction continue without adequate replenishment. Salts continue to diffuse into the reserve and some of the fresher water may become brackish (Falkland 2002*a*). Storm surges (and tsunamis) can overrun islands and pollute groundwater reserves with salt water and other contaminants. Uncertainties of future climate exacerbate the vulnerability of island groundwater reserves. Sea-level rise is not a critical threat as present-day storm surges can exceed predicted sea-level change estimates significantly in many regions (White *et al*. 2007). Indeed, small increases in base level may have a positive effect on many low limestone islands and induce a small increase in overall groundwater storage (Alam & Falkland 1997).

Extra care is needed to contain spillages from swimming pool chemicals, dry cleaning fluids, hydrocarbons, airport fire training foam and many other chemicals island society needs to import. Many island nations, including some of the Marshalls and the Kiribati islands, have seawater reticulation for water flush sewerage systems. These are an attractive option, but care needs to be taken to avoid leaks and to ensure that the treated waste is not allowed onto the land. Treated waste water from freshwater flush systems (e.g. at tourist compounds) may often be used to water gardens, but care is needed to monitor both quantity and quality of the discharge to avoid mobilization of bacteria, nutrients and other chemicals.

The hydrogeologist’s role in vulnerability assessment is similar to that for informing the managers of demand and supply. The hydrogeologist needs to identify those areas of ground below which groundwater is most vulnerable to surface pollution (and subsurface pollution where buried pipes and tanks, cemeteries, pit latrines and soakaways prevail) whereby groundwater vulnerability coupled with pollution pressures equals groundwater susceptability. Standard techniques such as DRASTIC (Aller *et al*. 1987) may be insensitive to the scale of small islands and vulnerability mapping is best done from first principles incorporating full knowledge of the island groundwater flow model. Maps of surface slope, vegetation type (land use), depth to water table, bedrock type and perceived permeability can be used to identify hotspots in which potentially polluting activities might be

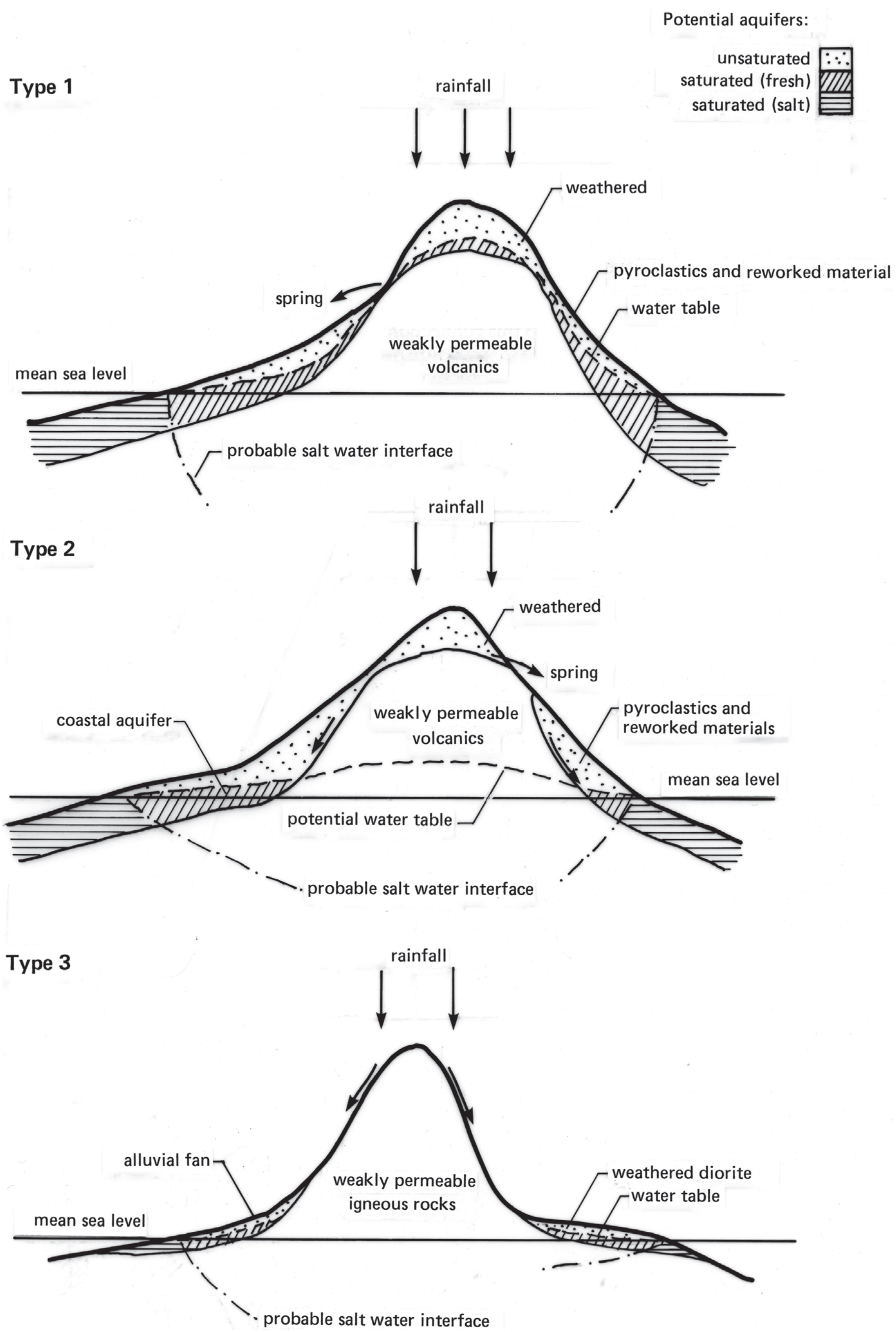

Fig. 2. Threefold division of 'high rise' volcanic islands in the West Indies after Robins *et al*. (1990).

prohibited, and less vulnerable areas where properly contained activities may be allowed. By using an informed personal judgement rather than the rigid algorithms prescribed in DRASTIC a vulnerability assessment can be made that also incorporates the hydrogeologist's knowledge and understanding of the island hydrology. The outcome can be transcribed into a simple map describing zones of vulnerability in terms of allowable activities that is meaningful to end users.

The Ghyben–Herzberg 'freshwater lens'

The concept that freshwater is less dense than seawater and can float above it was recorded in the writings of Pliny the Elder (23–79). Joseph Du Commun, teaching at the West Point Military Academy from 1818 to 1831, next identified the phenomenon (Carlston 1963) until the hydrostatic relationship between immiscible freshwater and salt-water bodies was independently investigated by Badon-Ghyben (1888–1889) and Herzberg (1901), and subsequently described as a dynamic equilibrium by Hubbert (1940). The subsequent landmark work in Bermuda by Vacher (1974, 1978) independently championed the concept of skimming freshwater contained in a 'lens' overlying salt water. The overall conclusion was, in theory, that the ratio of the elevation of the water table to the depth of the saline interface beneath sea level is about 1:40.

Practice has shown, for the most part, that the Ghyben–Herzberg theory has been found to apply only in part because the caveats of the theory require a uniform porous medium, infinite homogeneous aquifer, and many of the other standard Theisian controls. Given the

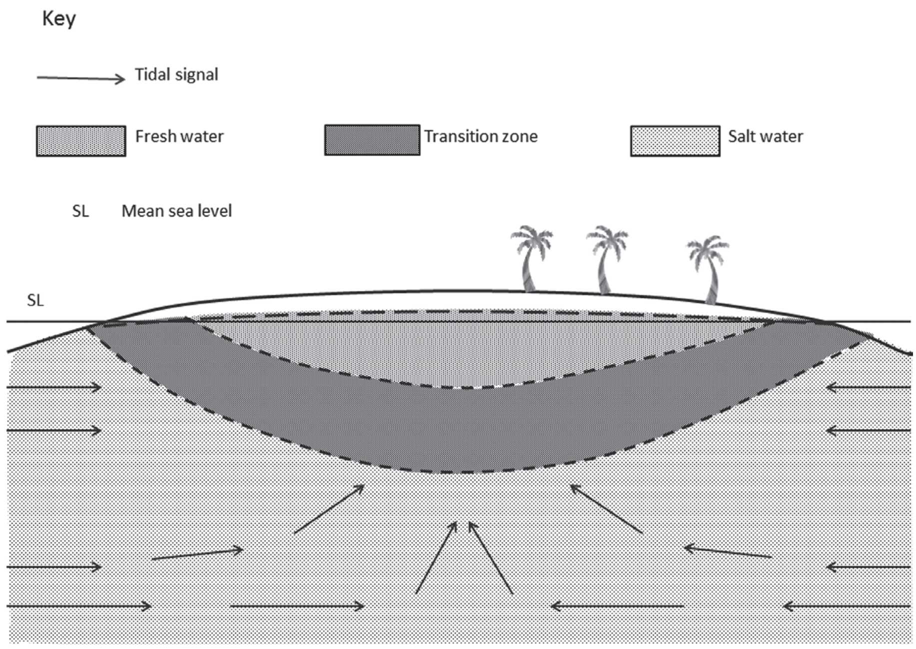

Fig. 3. Conceptual sketch across a small low-lying permeable island.

widespread occurrence of karst conduit systems in the islands that have developed at the present sea level as well as at lower relict sea levels, the application of the Ghyben–Herzberg principle is fraught with difficulty in many island situations. Conduit flow destroys the pressure balance, and the blue holes or cenotes of, for example, the Caribbean islands allow seawater ready access to the interior of an island. In practice, the saline water to freshwater interface is a dynamic diffusion zone, and the ratio of the elevation of the water table to the depth of the middle of the diffusion zone beneath sea level is normally much less than 1:40, in some places even less than 1:20 (Robins 2012).

The importance of the dynamic mixing or diffusion zone was recognized in the Caribbean at an early stage. Electrical resistivity soundings on Exuma were used by LRD (1974–1977) to reveal the salinity curves that are characteristic of a shallow freshwater lens. The thickness of the mixing zone in North Andros and Grand Bahama ranges up to 20 m reflecting tidal dynamics. Mixing can be enhanced by periodic imbalance of sea levels from one side of an island to another. Differences up to 0.3 m in sea level have been recorded across narrow limestone atoll islands in the Pacific caused by prevailing winds (Van der Velde *et al*. 2007) and the induced groundwater throughflow may cause significant perturbation at the saline water diffusion front.

The saline interface is a dispersion or diffusion zone that may be 20 m thick. As a consequence the simple static Ghyben–Herzberg theory is now in process of being superseded by dynamic dispersion models. These account for tidal lag and efficiency (time difference between and amplitude ratio of the water table fluctuations to sea tides), which vary with distance from the shore in low-lying limestone islands. Vertical propagation from tides is greatest towards the centre of an island and horizontal propagation greatest near the perimeter (Fig. 3), although tidally influenced rises and falls in groundwater level are greatest near the coast. Although the available dispersion modelling codes are complex, they replicate observed dispersion fronts and depths below sea level with considerable certainty (Falkland 2002*b*). SUTRA, available from the US Geological Survey (Voss *et al*. 1997), is the most commonly applied code for use in small islands and can be used both in a non-tidal and a tidal mode. The model applies a 2D ‘slice’ solution across an island, but more data intensive 3D codes are also available for use wherever data are available to support them. Generic dispersivity data can be selected to best fit the environment to be modelled.

Various rules based on the Ghyben–Herzberg principle are still applicable where the diffusion front can be approximated to a sharp line. Of these, the most common application is Henry’s Rule (Henry 1964) whereby the highest elevation of the water table in a long thin island or sand bar (H) is proportional to the width (a), according to the relationship

$$H^2 = \frac{Wa2}{4k(1+\alpha)} \tag{1}$$

where k is permeability, W is recharge per unit area and α is the density ratio of freshwater to seawater.

A similar relationship can be applied for islands that are approaching a compact circular shape of radius R by applying the Dupuit–Forchheimer approximations (Visher 1960):

$$H^2 = \frac{W}{4k(1+\alpha)}(R^2 - r^2) \tag{2}$$

where W is recharge (uniform and constant!) and r is the distance from the centre of the island for which the elevation of the water table (H) is to be determined. The highest part of the water table occurs when $r = 0$.

The hydrogeologist needs to be aware of the limitations of the simple Ghyben–Herzberg density ratio. In sensitive low-lying limestone and sand islands a dynamic model provides more reliable solutions than a simple static model, and ‘what if’ scenarios require to be based on the application of dynamic code such as SUTRA. In the case of high-rise hard rock islands, which are less sensitive to the location and width of the salt-water diffusion front, resort to Ghyben–Herzberg’s theory is likely to be adequate although heterogeneity may complicate matters.

Table 2. *Climate change scenario modelling at Shelter Island, NY (after Rozell & Wong 2010)*

Rainfall change	Sea-level rise (m)	Movement of saline interface	Water table rise (m)	Fresh groundwater store
15% increase	0.18	23 m seawards	0.27	3% increase
2% decrease	0.61	16 m landward	0.59	1% increase

Runoff and groundwater discharge estimation

Whereas a mainland catchment water balance can largely be observed and measured, the water balance of an island is partly unseen and, therefore, almost impossible to measure. In simple terms, effective rainfall equals runoff plus the change to the groundwater store. River hydrograph separation allows these two components to be determined as runoff and groundwater baseflow. In the island context, surface water catchments may offer only ephemeral flow reflecting a recent rainfall event and groundwater baseflow may largely occur not to the surface drainage system but directly beneath the beach to the sea or directly to coastal strips of mangrove. Simple estimates of the discharge per unit length of coast can be made using Darcian or Dupuit–Forchheimer strip models given some knowledge of the prevailing hydraulic parameters in the vicinity of the coast. Care is needed not to double account some of the groundwater discharge if the baseflow component is included in the surface water runoff (streamflow), a problem experienced with the water budget assessment of the hard rock island of Guernsey in the Channel islands (Robins *et al.* 2002). An island-wide groundwater flow model is the only way to establish the feasible range of the total groundwater baseflow.

A number of innovative techniques have been developed to quantify submarine discharges of groundwater including measurement of flux indicated by thermal and chemical gradients beneath the sea bed and mass balance of nutrients arriving offshore. The seepage meter (Lee 1977) has also been successfully deployed offshore although the question of representativeness of point source discharge to multi-layered systems always arises. Peterson *et al.* (2007) combined thermal imaging of cold groundwater discharges into the comparatively warm sea around Hawaii to identify focused conduit outflows from the volcanic onshore aquifer. Mass-balance calculations using natural tracers, in this case salinity and radon, were then applied to quantify the observed discharge plumes. The technique is applicable only to significant discharges and the case study described outflows of the order of $10^3 m^3 day^{-1}$.

Coastal and offshore discharge is an issue that the hydrogeologist needs to focus on to formalize methods that will quantify groundwater baseflow from island aquifers. Key meteorological information such as potential evaporation and rainfall distribution are often unavailable for small islands and it is important to constrain likely effective rainfall if offshore groundwater discharge is not known. Continuing investigation of small island water balances will, no doubt, provide applicable methods for measuring offshore discharge. At present, however, this remains the key challenge for workers in this field.

Base-level change

Sea-level rise is perceived as a potential threat to the well-being of communities on low-relief islands. For the most part, islands benefit from a slight increase in groundwater storage although some very low-relief islands will be more vulnerable to storm surge damage. Conversely, the seawater diffusion zone is likely to move inland. A number of studies have been carried out and a case study investigation on Shelter Island, New York State, which comprises sand grade material, is typical. A variable density transient groundwater flow model was run for the extreme climate change scenarios summarized in Table 2 (Rozell & Wong 2010). Both promote an increase in the groundwater store; in the worst-case scenario the landward movement of the saline interface is more than balanced by the projected rise in the water table.

Water table rise reduces the thickness of the unsaturated zone and may even create wetlands in low-elevation areas. These both have a downside: reduction in the unsaturated zone increases the vulnerability of the aquifer to pollution from surface and subsurface sources, and wetlands act as groundwater sinks in areas of high potential evaporation comparative to overall long-term rainfall. Some wetlands on tropical low-lying islands, for example Anguilla in the West Indies, are hypersaline.

Although perceived as a threat to island communities, base-level rise is not an immediate threat and is secondary to the vulnerability of island aquifers to current adverse natural occurrences and anthropogenic abuse of the environment. The hydrogeologist, for the moment, is best deployed addressing these present-day threats rather than put to predictive work based on as yet uncertain climate change predictions.

Discussion and conclusions

Classification of small islands, at a minimum, can be simplified to just high- and low-elevation islands (Robins & Lawrence 2000). The key to the hydrogeological understanding of islands is the division between low-lying permeable islands with a distinct salt-water diffusion zone beneath them and a near absence of runoff and higher elevation hard rock islands usually characterized by runoff and a peripheral saline interface. Variations and complexities caused by layering and perching occur in both types, and common also to both are the pressures of demand and availability of a finite resource.

The variety of island types in both low and high groups is considerable. Some of the high islands have deeply incised valleys with sediment infill complete with saline wedges thinning inland. Others may be raised limestone islands with elevated relict karst horizons. Such is the variety of small island environments that a bespoke investigatory method has to be applied to every situation although lessons can be learnt from previous studies in similar small island types.

There are, however, some generic themes common to all small islands. Groundwater flow modelling may not always be able to cope with the small island scale and typical data scarcity, and novel flow and transport modelling techniques may need to be applied (Praveena *et al.* 2010). Fractured volcanic rocks and karstic limestones cannot be resolved easily by a porous media flow model of a small island because conduit flow systems are likely to dominate the flow regime. This is not so critical at mainland basin scale, where the hydraulics of the fracture flow system merges towards that of a porous medium over longer flow paths. It is also difficult to assign a realistic permeability in fractured rocks, as test pumping reflects borehole connectivity to the fracture system rather than an island-wide value of permeability. Such data scarcity means that the model solutions may not be unique.

Above all, the key generic island lesson is data availability and representativeness. There are rarely enough data. The initial role of the hydrogeologist is to complete the conceptualization and initial water balance with what information is available and then to decide what further work is needed. The variety of island types means that the hydrogeologist might resort to meteorological monitoring as much as groundwater level monitoring and spring discharge measurement, electrical resistivity surveying as much as tracer work; indeed, every available technique needs to be considered to improve understanding of the hydrology of a small island (Ruppel *et al*. 2000; Jocson *et al*. 2002; Jones & Banner 2003).

Small island hydrogeology requires the application of the same methods that mainland basin studies use save that many are constrained by scale and data availability. Although modern computing codes allow comprehensive synthesis of island-wide flow systems, the models themselves may be supported by several variables, including effective rainfall, coastal baseflow discharge and permeability, particularly of fractured or karst systems. Model solutions, therefore, may not be unique unless such variables can be constrained by further cost-effective investigation. This may include any of the modern techniques, such as isotope chemistry and groundwater dating tools or application of data loggers, that are available to the hydrogeologist, who has to decide which are best deployed to cost-effectively maximize the understanding of the hydrogeology of the island system. Underpinning these activities is the need for the hydrogeologist to be able to inform managers how best to optimize the available resource and what messages need to be given to the community to safeguard the resource.

Data scarcity and uncertainty are major problems and effort may be better spent on data gathering rather than modelling. Representative measurement of rainfall and evaporation, particularly on high rise islands, generates uncertainty that is not readily quantified. Permeability of karst and fractured aquifers is also uncertain. However, measurement of baseflow at the periphery of a small island is the cause of greatest uncertainty and it is this area that current research aims to better constrain in the future.

Despite the difficulties inherent in their hydrogeological investigations, small islands offer some interesting and exciting challenges. Often working to tight budgets, the hydrogeologist needs to apply as many investigatory methods as resources allow to develop the initial conceptual model and water balance into a tested and robust description of the groundwater system, which ultimately can form the basis of a management decision support system. Small island hydrogeological techniques have improved considerably in the last 20 years, not least by the application of powerful digital analytical codes, but must now start to advance as much again for hydrogeologists to be able to help the populations of those small island states that are densely populated and receive only erratic and unreliable rainfall recharge.

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References

Alam, K. & Falkland, A. 1997. *Vulnerability to climate change of the Bonriki freshwater lens, Tarawa. Ecowise Environmental, Canberra*. Report for Ministry of Environment and Social Development, Kiribati, Technical Report, **HWR97/11**.

Aller, L., Bennett, T., Lehr, J.H., Petty, R.J. & Hackett, G. 1987. *DRASTIC, a standardized system for evaluating groundwater pollution potential using hydrogeologic settings*. US Environmental Protection Agency Report, **600/2-87-035**.

Badon-Ghyben, W. 1888–1889. Nota in Verband met de Voorgenomen Putboring nabij Amsterdam. *Tijdschrift van het Koninklijk Instituut van Ingenieurs*. US EPA report.

Carlston, C.W. 1963. An early American statement of the Badon–Herzberg Principle of static fresh-water–salt-water balance. *American Journal of Science*, **261**, 88–91.

Crenman, L. 2002. Awareness. *In*: Carpenter, C., Stubbs, J. & Overmars, M. (eds) *Proceedings of the Pacific Regional Consultation on Water in Small Island Countries, Suva, Fiji*. Asian Development Bank–South Pacific Applied Geoscience Commission. Suva, Fiji, 9–66.

Dillon, P. 1997. *Groundwater pollution by sanitation on tropical islands*. UNESCO—International Hydrological Programme V, Technical Documents in Hydrology, **6**.

Falkland, A. (ed.) 1991. *Hydrology and water resources of small islands: A practical guide*. UNESCO. Paris.

Falkland, A. 2002*a*. Water resource management. *In*: Carpenter, C., Stubbs, JC. & Overmars, M. (eds) *Proceedings of the Pacific Regional Consultation on Water in Small Island Countries, Suva, Fiji*. Asian Development Bank–South Pacific Applied Geoscience Commission. Suva, Fiji.

Falkland, A. 2002*b*. Tropical island hydrology and water resources current knowledge and future needs. *In*: *Second International Colloquium on Hydrology and Water Management in the Humid Tropics. Panama City, 1999*. UNESCO—International Hydrological Programme V, Technical Documents in Hydrology, **52**, 237–298.

Henry, H.R. 1964. Effects of dispersion on salt encroachment in coastal aquifers. *In*: Cooper, H.H., Kohout, F.A., Henry, H.R. & Glover, R.E. (eds) *Seawater in Coastal Aquifers*. US Geological Survey Water Supply Paper, **1613-C**, 70–83.

Herzberg, A. 1901. Die Wasserversorgung einiger Nordseebader. *Journal für Gasbeleuchtung und Wasserversorgung*, **44**, 815–819.

Hubbert, M.K. 1940. The theory of groundwater motion. *Journal of Geology*, **48**, 785–944.

Jocson, J.M.U., Jenson, J.W. & Contractor, D.N. 2002. Recharge and aquifer response: Northern Guam Lens aquifer, Guam, Mariana islands. *Journal of Hydrology*, **260**, 231–254.

Jones, I.C. & Banner, J.L. 2003. Estimating thresholds in tropical Karst island aquifers: Barbados, Puerto Rico and Guam. *Journal of Hydrology*, **278**, 131–143.

Lee, D.R. 1977. A device for measuring seepage flux in lakes and estuaries. *Limnology and Oceonography*, **22**, 140–147.

LRD 1974–1977. *Land Resources of the Commonwealth of the Bahamas*. Land Resources Division, Tolworth.

Martin-Kaye, P.H. 1959. *Reports on the geology of the Leeward and British Virgin islands*. Voice Publishing Company, Castries, St. Lucia.

Matalas, N.C. 1987. Hydrology in an island–continent context. *In*: McLaren, D.J. & Skinner, B.J. (eds) *Resources and World Development*. S. Bernhard Dahlem Konferenzen, Berlin, 569–592.

Matalas, N.C. & Grossling, B.F. 1996. *Habitat and Environment of Islands*. US Geological Survey Professional Paper, **1590**.

Metutera, T. 2002. Water management in Kiribati with special emphasis on groundwater development using infiltration galleries. *In*: Carpenter, C., Stubbs, J. & Overmars, M. (eds) *Proceedings of the Pacific Region Consultation on Water in Small Island Countries, Suva, Fiji*. Asian Development Bank–South Pacific Geoscience Commission. Suva, Fiji.

Moglia, M., Alexander, K.S., *et al*. 2008. Regional and country scale water resource assessment; informing investments in future water supply in the Asia Pacific region—a decision support tool. CSIRO: Australia, Water for a Healthy Country National Research Flagship. *World Wide Web Address:* http://scholar.googleusercontent.com/scholar?q=cache:Wj419i6bvtUJ:scholar.google.com/&;hl=en&as_sdt=2005&sciodt=0,5.

Mowlabucus, M.F. 2002. A note on the hydrology of small islands. *In*: *Proceedings of the Second International Colloquium on Hydrology and Water Management in the Humid Tropics, Panama City*, UNESCO-International Hydrological Programme V, Technical documents in Hydrogeology, **52,** 341–349.

Peterson, R., Burnett, W.C., Glenn, C.R. & Johnson, A.J. 2007. A box model to quantify groundwater discharge along the Kona coast of Hawaii using natural tracers. *In*: Sanford, W., Langevin, C., Polemio, M. & Povenic, P. (eds) *A New Focus on Groundwater–Seawater Interactions*. IAHS Publications, **312**, 142–149.

Praveena, S.M., Abdullah, M.H. & Aris, A.Z. 2010. Modeling for equitable groundwater management. *International Journal of Environmental Research*, **4**, 415–426.

Robins, N.S. 2012. Island hydrogeology: Highlights from early experience in the West Indies and Bermuda. *In*: Howden, N. & Mather, J.D. (eds) *History of Hydrogeology*. IAH International Contributions to Hydrogeology, **28**, 29–40.

Robins, N.S. & Lawrence, A.R. 2000. Some hydrogeological problems peculiar to various types of small islands. *Water and Environment Journal*, **14**, 341–346.

Robins, N.S. & Smedley, P.L. 1994. Hydrogeology and hydrogeochemistry of a small, hard rock island—the heavily stressed aquifer of Jersey. *Journal of Hydrology*, **163**, 249–269.

Robins, N.S., Lawrence, A.R. & Cripps, A.C. 1990. Problems of groundwater development in small volcanic islands in the Eastern Caribbean. *In*: Krishna, J.H., Quiñones-Aponte, V., Gómez-Gómez, F. & Morris, G. (eds) *Tropical Hydrology and Caribbean Water Resources, AWRA, San Juan*, American Water Resources Association, Bethesda, Maryland, 257–267.

Robins, N.S., Griffiths, K.J., Merrin, P.D. & Darling, W.G. 2002. Sustainable groundwater resources in a hard-rock island aquifer—the Channel Island of Guernsey. *In*: Hiscock, K.M., Rivett, M.O. & Davison, R.M. (eds) *Sustainable Groundwater Development*. *Geological Society, London, Special Publications*, **193**, 121–132.

Rozell, D.J. & Wong, T.-f. 2010. Effects of climate change on groundwater resources at Shelter Island, New York state, USA. *Hydrogeology Journal*, **18**, 1657–1665.

Ruppel, C., Schultz, G. & Kruse, S. 2000. Anomalous fresh water lens morphology on a strip barrier island. *Ground Water*, **38**, 872–881.

Sakura, Y., Tang, C., Yoshioka, R. & Ihibashi, H. 2003. Intensive use of groundwater in some areas of China and Japan. *In*: Liamas, R. & Custodio, E. (eds) *Intensive Use of Groundwater*. Balkema, Rotterdam, 337–353.

Stuart, M.E., Maurice, L., *et al.* 2010. Groundwater residence time and movement in the Maltese islands—a geochemical approach. *Applied Geochemistry*, **25**, 609–620.

Vacher, H.L. 1974. *Ground water hydrology of Bermuda*. Technical Report, Public Works Department, Bermuda.

Vacher, H.L. 1978. Hydrogeology of Bermuda: Significance of an across-the-island variation in permeability. *Journal of Hydrology*, **39**, 207–226.

Vacher, H.L. & Quinn, T.M. 2004. Introduction: Varieties of carbonate islands and historical perspective. *In*: Vacher, H.L. & Quinn, T.M. (eds) *Geology and Hydrogeology of Carbonate Islands*. Elsevier, Amsterdam, 1–34.

Van der Velde, M., Vakasiuola, M., *et al.* 2007. Climatic variation, recharge and freshwater lens salinity of a coral atoll in the Pacific Ocean. *In*: Sanford, W., Langevin, C., Polemio, M. & Povenic, P. (eds) *A New Focus on Groundwater–Seawater Interactions*. IAHS Publications, **312**, 244–255.

Visher, F.N. 1960. *Qualitative Hydrodynamics within an Oceanic Island*. International Association of Scientific Hydrology, Publication, **52**, 470–477.

Voss, C.I., Boldt, D. & Shapiro, A.M. 1997. *A graphical user interface for the US Geological Survey's SUTRA code using Argus One (for simulation of variable density saturated–unsaturated ground water flow with solute energy transport)*. US Geological Survey Open-File Report, **97-421**.

Watson, R.T., Zinyowera, M.C., Moss, R.H. & Dukkon, D.J. (eds) 1998. *Regional Impacts of Climate Change, an Assessment of Vulnerability*, Cambridge University Press, Cambridge.

White, I., Falkland, F., *et al.* 2007. Challenges in freshwater management in low coral atolls. *Journal of Cleaner Production*, **15**, 1522–1528.

White, I., Falkland, A., Crennan, L., Jones, P., Etuati, B. & Metai, E. 1999. *Issues, traditions and conflicts in groundwater use and management*. UNESCO—International Hydrological Programme V, Theme 6, Technical Documents in Hydrology, **26**.

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